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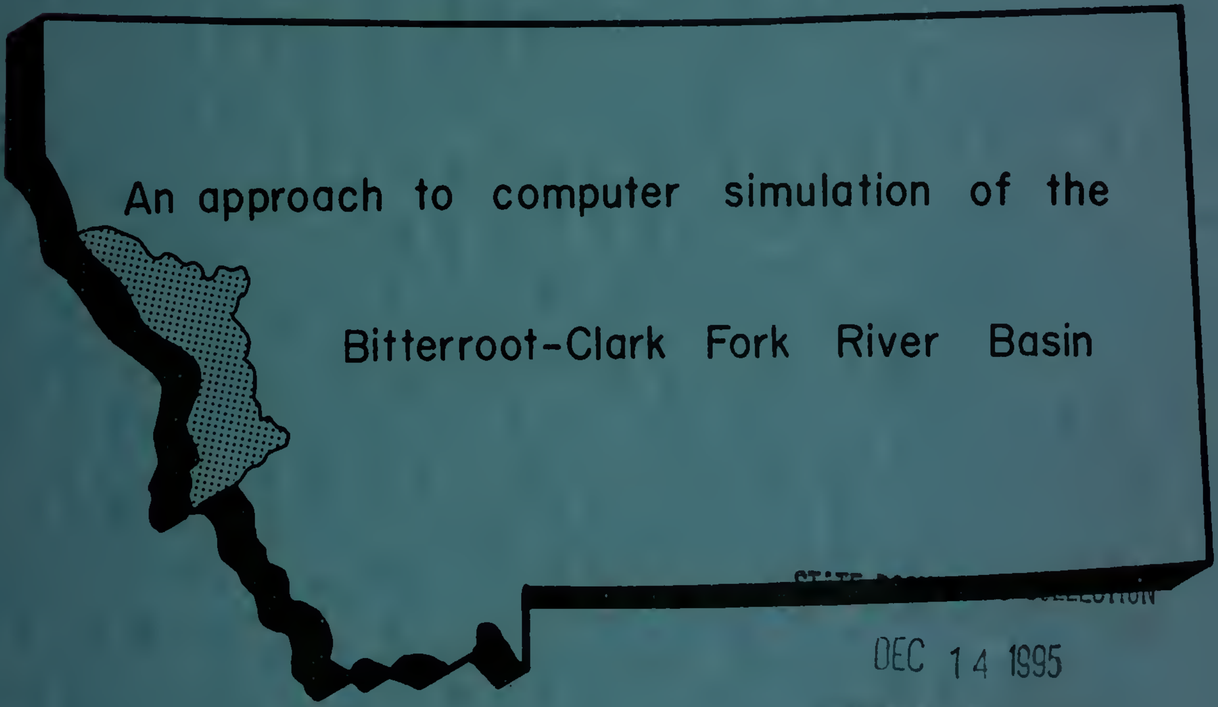
River basin modeling: an approach to computer simulation of the Bitterroot-Clark River Basin

"A Comprehensive Water and Related Land Resources Plan for the State of Montana"

RIVER BASIN MODELING



An approach to computer simulation of the Bitterroot-Clark Fork River Basin

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"A Comprehensive Water and Related Land Resources Plan for the State of Montana"

RIVER BASIN MODELING

An approach to computer simulation of the Bitterroot-Clark Fork River Basin

APRIL 1971

The work upon which this report is based was supported primarily by funds provided by the Montana Legislature and with funds furnished by the Water Resources Council under Title III of the Water Resources Planning Act of 1965 (Public Law 89-80).

FOREWARD

This publication, prepared by the Planning Division of the Montana Water Resources Board, is a report on the use of systems analysis and computer modeling in the field of water resources planning.

This study, utilizing funds provided by Montana's 1969 Legislature under the Water Resources Planning Act of 1967, and those obtained from the Federal Water Resources Council under Public Law 89-80, is one in a planned series of water utilization studies in the preparation of Montana's statewide comprehensive water and related land resources plan.

The data contained herein, and that furnished through further use of the model, will in part lay the foundation for the water needs phase of the State Water Plan and will provide for the utilization of data collected under the inventory phase of the plan.

DOUGLAS G. SMITH
Director
Montana Water Resources Board

TABLE OF CONTENTS

Introduction

Simulation-General 1

Background of the Study 3

History of the Area 4

Economy of the Area 5

Land Area & Population 6

Bitterroot Clark Fork River Basin Simulation Model

System Definition 7

Preparation of Hydrologic Data 10

Definition of System Design 12

Operating Procedure 14

Operating Results to be Achieved 16

Conclusion 17

Conjunctive Use of Groundwater as an Alternative to Surface Water . . . 18

Selected References 21

TABLES

Table 1 . . . . Period of Stream Discharge Record

2 . . . . Land Classification

3 . . . . Diversion Requirement

FIGURES

Figure 1 . . . . Planning a Water Resource System

2 . . . . Base Map of Study Area & Subareas

4 . . . . Existing Irrigation & Projects

5 . . . . Potential Irrigation & Projects

6 . . . . Operating Procedure

INTRODUCTION

Simulation-General

Use of models for simulation is not a recent development, but the use of mathematical models is. Models used in water resources and other applications can be classified into three groups, the iconic or look-alike models used in the engineering design of water-use structures, the analog model that has been extensively applied in ground water and other fields, and symbolic computer models. Symbolic models (using the mathematical approach) comprise a class having two subdivisions, the first of which is the analytical model that can often be solved without the use of computer methods, and the second is the simulation model.

In general, simulation and analytical models use a process by which it is possible to duplicate the essential characteristics of a system or activity without actually attaining reality itself. Problems in water resources design are generally beyond the capability of analytical methods due to the complex relationships and the interdependencies that exist among the design variables. Therefore, simulation is often the only way these problems in both the design and management of water resource systems can be solved. Figure 1 schematically shows the steps in planning a water resource system.

This project report records the effects of a simulated development of the irrigable land in the Bitterroot Valley using both present and proposed systems of water storage and distribution. Besides a study of the valley, the report deals briefly with the effects of stream discharge upon downstream areas of irrigable land.

The techniques referred to and used in this study could be considered as being concerned with model building and manipulation so as to achieve a predetermined aim. Model building (or simulation) is based on the idea that the important properties of a system to be studied can be built into a model which retains the essential characteristics of that system.

PLANNING A WATER RESOURCE SYSTEM

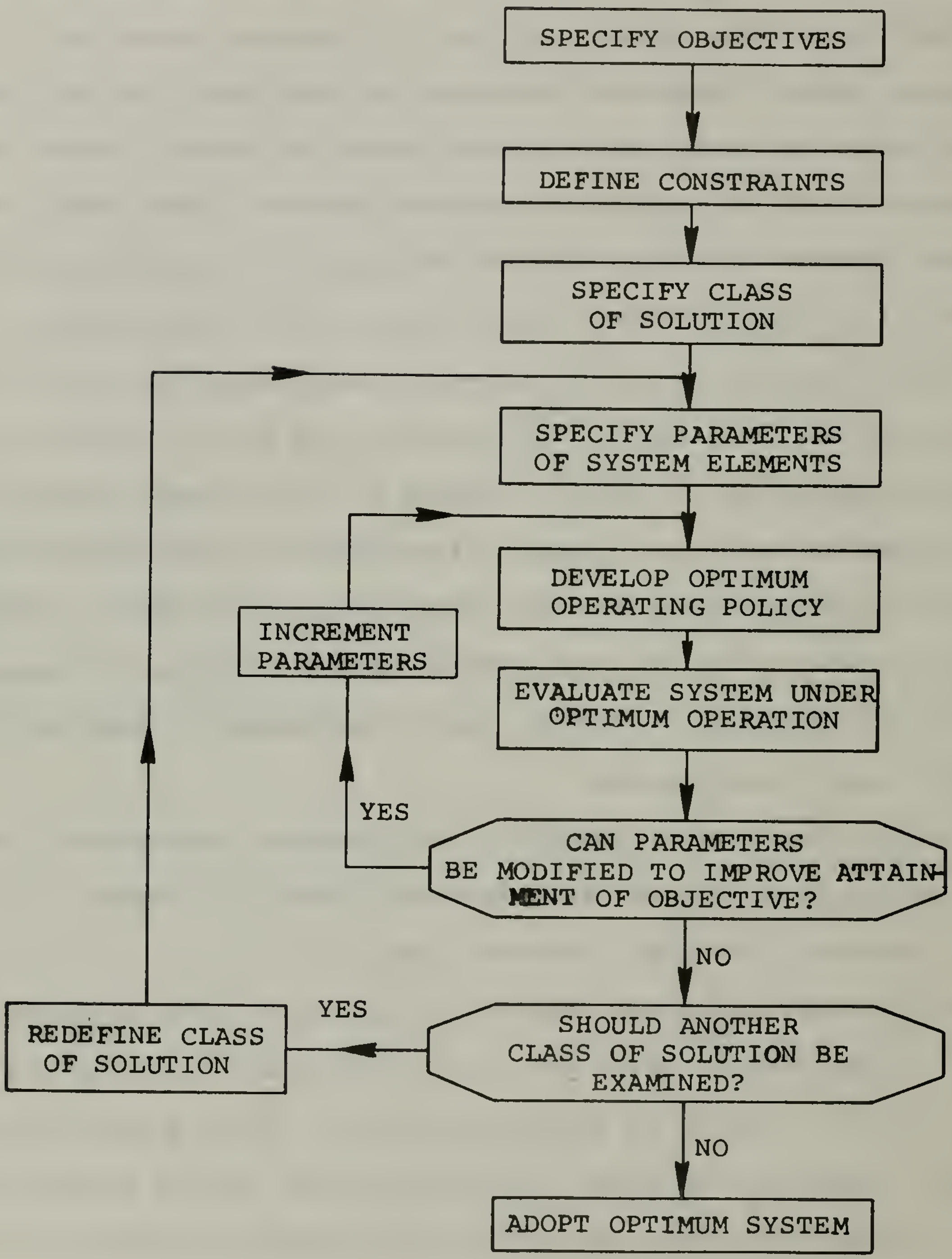

SPECIFY OBJECTIVES
DEFINE CONSTRAINTS
SPECIFY CLASS OF SOLUTION
SPECIFY PARAMETERS OF SYSTEM ELEMENTS
DEVELOP OPTIMUM OPERATING POLICY
INCREMENT PARAMETERS
EVALUATE SYSTEM UNDER OPTIMUM OPERATION
YES
CAN PARAMETERS BE MODIFIED TO IMPROVE ATTAINMENT OF OBJECTIVE?
NO
YES
REDEFINE CLASS OF SOLUTION
SHOULD ANOTHER CLASS OF SOLUTION BE EXAMINED?
NO
ADOPT OPTIMUM SYSTEM

FIGURE 1

Model building in some form has been used for a very long time. The problem of using some models is that they are complex, expensive to construct, and difficult to modify if it is desired to study the effect of a change of dimension as is the usual case.

In this project, an important aim was to use mathematical modeling or computer simulation so that it would be possible to change the model to reflect actual or proposed changes in either the physical system or its operating plan and thus be able to evaluate the results of these changes, whether they be imposed for legal, administrative, or other reasons.

This report was designed to demonstrate the feasibility and explain the processes involved in adapting systems analysis techniques to river basin planning. It was not designed as a technical paper relating to the computer simulation runs which have been and will be forthcoming, but merely explains the preliminary steps taken in preparation for using the system.

Many different simulation models have been constructed over the past years to study water by computer methods. These vary from those large complex models such as the Stanford University Watershed Model to those for individual watersheds such as the Bitterroot-Clark Fork model presented here.

The water resources of Montana have multiple uses, being used for irrigation, municipal and industrial purposes, and recreation, as well as playing a part in preserving a suitable environment for fish and wildlife and preserving scenic values throughout the state.

The mark of a good model is that it represents these significant factors involved in the situation being modeled, but omits or simplifies consideration of factors that are of lesser importance.

As the water needs study of Montana's state water and related land resources plan begins to take shape, these factors will be utilized in this and subsequent models to present an overall picture of proper management and utilization of our water resources.

Background of the Study

In August, 1970, the Nevada Center for Water Resources Research of the Desert Research Institute, University of Nevada at Reno, proposed to construct and operate for the Montana Water Resources Board a computer model to demonstrate maximum development of land within the limits of an available water resource for the Bitterroot Valley and the reach of the Clark Fork Valley from the Bitterroot confluence at Missoula to St. Regis, Montana. This model was developed, not only to meet the above objective, but to demonstrate the validity of the use of river basin modeling in water resources planning in Montana. This computer analysis of stream flows, and potentially irrigable and presently irrigated lands, demonstrates the effects of present stream management, storage programs, and irrigation procedures on the efficient use of water for meeting present and future demands.

A simulation model was used to determine optimum amounts of storage necessary to satisfy water requirements for various levels of development of irrigable lands within the area. The model considers the major hydrologic inputs and outputs for the area, such as surface water inflow and outflow and groundwater discharge and recharge, and is constructed so that streamflow of the Clark Fork River above Missoula could be an input to the model.

Existing streamflow was utilized to as great an extent as possible, and data was synthesized for areas where insufficient or no data existed. The model is operated over a time horizon of 25 years with each year divided into seasons which reflect the availability and use of water.

The specific methodologies used include orthodox mathematical approaches developed by many agencies including the U.S. Army Corps of Engineers, the U.C.L.A. Civil Engineering Department, the Maas, et. al. group at Harvard University, and the Desert Research Institute of Nevada.

During the project period the phases of work were delivered to the Water Resources Board on a monthly basis and members of the staff of the Board actively assisted in gathering, compiling, and analyzing the data. One of the side effects of this modeling exercise was the training of the Water Board staff in the techniques and methods of river basin modeling and the demonstration of the practicality of using systems analysis in water resources planning.

Twenty trial runs have been made to date: ten each for two sets of assumptions based on existing and potential water and land development. Because these runs are largely unconstrained, that is, the only constraint being on the development of potential irrigable lands, the results of these runs are not included in this report. Additional constraints must be considered, and assumptions made, for future runs to be valid. One can see, however, the effects of optimum development are easily recognizable from the use which has been made of the model to date.

History of the Area

The history of the study area centers around the travel of the early civilization into and out of Montana and the Bitterroot Valley.

Following the Lewis and Clark expedition through the area in 1805, little activity of the white man was evident until religious missionaries entered the area in the 1830's in an effort to convert the Indians to Christianity.

Settlement of the area continued, based on stockraising, farming, and some lumbering and mining which was limited considerably by problems with the Indians. With the departure of the Indian problem and the rapid growth of Montana in the 1880's, the development of the area accelerated. The coming of the Northern Pacific Railway in 1883, the construction of the Missoula and Bitterroot Valley Railway to Grantsdale in 1887, and the Milwaukee Road in 1908 were of paramount importance for they afforded the farmers greater opportunities for disposing of their crops and opened up the forest resources of the valleys for exploitation to satisfy the tremendous demands of the mining community.

The discovery of gold in 1868 resulted in the rapid growth of the St. Regis Valley and with the completion of the Northern Pacific Railway in 1891, the lumber and sawmill industry boosted the sagging mining economy of the area around Superior and St. Regis.

Montana territory was created in May, 1864, and an effective government was created for Missoula County in early 1865. Not until 1893 did the Bitterroot Valley have sufficient population to warrant separate existence, and the state legislature in that year created Ravalli County and in 1898 the town of Hamilton won the bid for county seat.

Economy of the Area

Ravalli County, since 1910, has been relatively static in respect to population growth and economic makeup. The county remains a rich and prosperous agricultural region with numerous small communities to serve the immediate needs of the population. The tourist industry has become a more important factor of the economy and with the influx into the area of many retired and semi-retired persons, a noticeable change is evident throughout the valley. Logging is still a very prominent industry of the area but has diminished in relative importance since 1910. Agriculture is still the prime "industry" in the Bitterroot Valley.

Missoula County resembles Ravalli County in that it was first settled because of rich farming lands, with mining and logging destined to be secondary factors in the county's settlement and development. The nearest large center of trade, industry and air travel for the entire study area is at Missoula.

Lumber and the wood products industry have grown in Missoula County more rapidly and to a greater extent than anywhere else in Montana. The city and surrounding smaller towns support several large sawmills as well as one pulp and paper mill, one forest products plant at Bonner, and numerous wood product manufacturing plants.

Agriculture has played only a minor role in the settlement and economy of Mineral County. The heavily timbered valleys and hillsides precluded any extensive development of farming and stockraising. Most of the valley bottoms are not extensive enough for any large scale ranching and farming operations. The county has good access to rail, highway, and bus transportation facilities. No commercial air service exists within the county.

Land Area & Population

Ravalli County covers a land area of 2410 square miles, over 75 percent of which is publicly owned.

The change in small farm ownerships being absorbed by larger farms, and the decrease in lumbering industries, caused a decline in population until 1960. Since 1960, the influx of rural non-farm population into Ravalli County has caused an all-time high of 14,409 people in 1970.

Missoula County encompasses over 2614 square miles of land area, only a portion of which is in the study area, and has a population of 58,263 persons, an increase of 30.5 percent over 1960, of which over 44,500 live in the immediate Missoula city area.

Mineral County covers a land area of 1223 square miles and has a 1970 population of 2958 people, declining 2.6 percent from 1960.

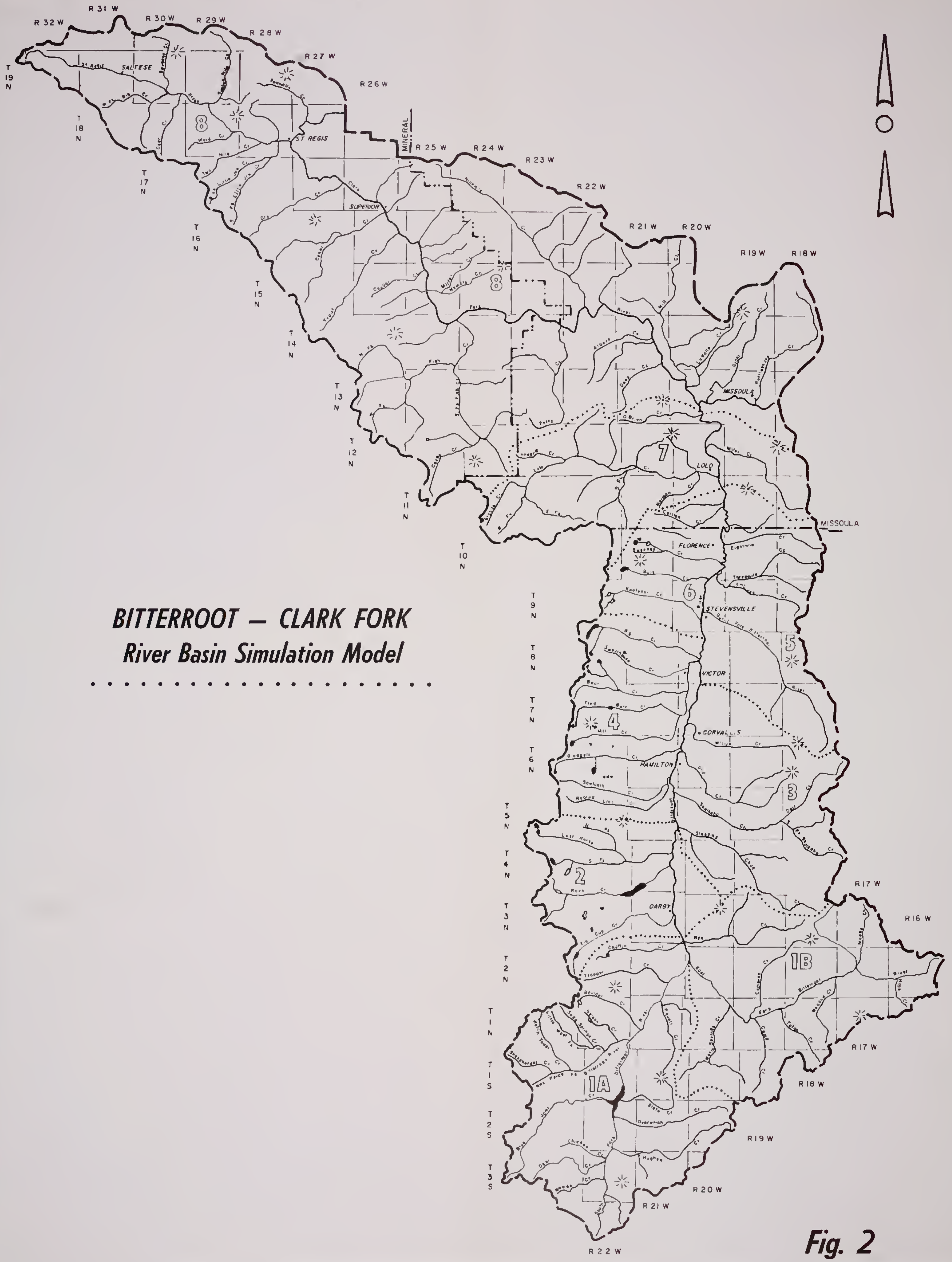
System Definition

The simulation approach used in this study can best be explained by outlining the steps necessary to carry out the study, together with some of the problems encountered.

It is necessary to first define the system boundaries in space and time and then define a level of interest or of feasible discrimination. While it is easy to set system boundaries, the best boundary choice is not always clear. A river basin is an obvious unit to use, but this may not be enough. Physical links between basins, when they exist, are obvious pointers to indicate that the linked basins should be considered together. For this particular study the system boundaries are defined as the Bitterroot Valley and that portion of the Clark Fork extending from just above Missoula to St. Regis (Figure 2). The Bitterroot River basin was an obvious unit for the planning purpose of this study, but the reach of the Clark Fork was included to evaluate the downstream effects of proposed changes made on the Bitterroot River.

This decision solves the system boundaries problem, but the planner is still faced with the "level of detail" problem. System definition must include all of the factors of water use and control. With an extremely detailed model, even the small uses of water will be identified and accounted for in the model. There is no limit to the items that can be included in such a model, unless it is recognized that other input data on which the system is based has limited accuracy. Parts of the water resource system whose behavior is required only on an overall basis can be aggregated or lumped.

System definition also includes recognition of all of the locations for which data on water availability and water use is given, as well as the sites at which water control will possibly be undertaken.



BITTERROOT — CLARK FORK
River Basin Simulation Model

Fig. 2

The study area as defined has been further subdivided into eight subareas to allow examination of the system in a finer level of detail and to enable, through use of the model, consideration of major use and control points. (Figure 2). The following criteria were used to delineate the subareas: 1) presently irrigated land, 2) potentially irrigable land, 3) existing storage and water distribution systems, and 4) potential projects affecting water supply.

Subarea 1 is the major headwater area of the Bitterroot River. The average annual discharge from this area, Bitterroot River near Darby, is 655,200 acre-feet which is approximately 38 percent of the total Bitterroot River discharge. The area includes both the West Fork (1A) and East Fork (1B) of the Bitterroot River as well as Painted Rocks Reservoir Ⓐ which has a capacity of 32,362 acre-feet. Painted Rocks reservoir on the West Fork, together with the proposed (60,000 acre feet) Upper Sula reservoir ①, on the East Fork, could be combined to provide regulation on the river's main stem during late irrigation season and thus provide supplemental water to downstream areas.

Subarea 2 is that area extending for north of Chaffin Creek to Ward Mountain on the west side of the river. Major sources of irrigation water in this area are Tin Cup, Rock and Lost Horse Creeks. Area 2 also includes Lake Como Ⓑ an irrigation reservoir situated on Rock Creek with an active capacity of 33,000 acre-feet, which has been used to supply the Bitterroot Canal. The U.S. Bureau of Reclamation has proposed enlargement of Lake Como ② to 53,600 acre-feet to provide supplemental water to the west side of the Valley which serves to make this area a distinct part of the simulation model.

Subarea 3 extends along the east side of the Valley from Deer Mountain to Palisade Mountain. The sources of supply for the irrigated lands in subarea 3 are the natural inflows from Sleeping Child, Skalkaho, Gird, and Willow Creeks, plus several major canals which divert water from the river and Lake Como. No major storage facilities exist in Subarea 3 nor are any sizable storages proposed.

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Subarea 4 extends along the west side of the Valley from Ward Mountain to north of Big Creek. Irrigation supply is primarily from eight major creeks and many smaller ones draining out of the Bitterroot Mountains. Several proposals have been made that would increase the late season supply. Among these proposals are the Westside Highline Canal, the Woodside Canal, and a storage reservoir on Blodgett Creek ③ with a capacity of 10,500 acre-feet.

Subarea 5, adjacent to Subarea 3, includes the remainder of the Bitterroot Valley east of the river to just south of Lolo. The natural supply for this area consists primarily of the Burnt Fork of Bitterroot River plus smaller tributaries, Ambrose, Threemile, and Eightmile Creeks. This area is also served by several major canals which divert water from either the main river channel or upstream tributaries. There are presently no major storage facilities in this area but a storage facility situated on Burnt Fork ④ with a capacity of 13,000 acre-feet of storage has been suggested.

Subarea 6 is an area similar to Subarea 4 covering an area west of the Bitterroot River from just north of Big Creek to a point south of Lolo. The natural supply for this area includes several major streams such as Kootenai, Bass, Sweeney, and Carlton, none of which has a major storage facility or proposed storage site.

Subarea 7 lies along the northern end of the Bitterroot Valley and includes the Lolo Creek and Miller Creek drainages, but the proposed Lolo Creek dam ⑤ and reservoir with a capacity of 135,000 acre-feet could have an effect on downstream areas which should be considered.

All the area below Missoula to St. Regis (Subarea 8) was considered as a single area. Only the effects of change within the Bitterroot Valley on this area were examined. Input from the Upper Clark Fork Drainage was not considered since this area itself is complex and would require simulation in much finer detail.

In addition, system definition also involves time in two ways. Modeling the water resource history of a system is the best way of proving a model; but simulation has its greatest usefulness as a predictive device to determine the effect of design and management proposals on future water use.

For this purpose it is necessary to recognize changes in water use in terms of type of use and volumes and points of diversion over the time span for which the model will be used. A further aspect of the time problem is the specification of an appropriate time period for modeling purposes. For the objectives of this study, and the quantity of water available for supply purposes, a time interval of a month is satisfactory. Therefore, it was assumed that it is satisfactory to use average values of water use, and supply, which will apply for the duration of each time period; 1 month. For some other related phenomena such as floods, a time period of a month is too long.

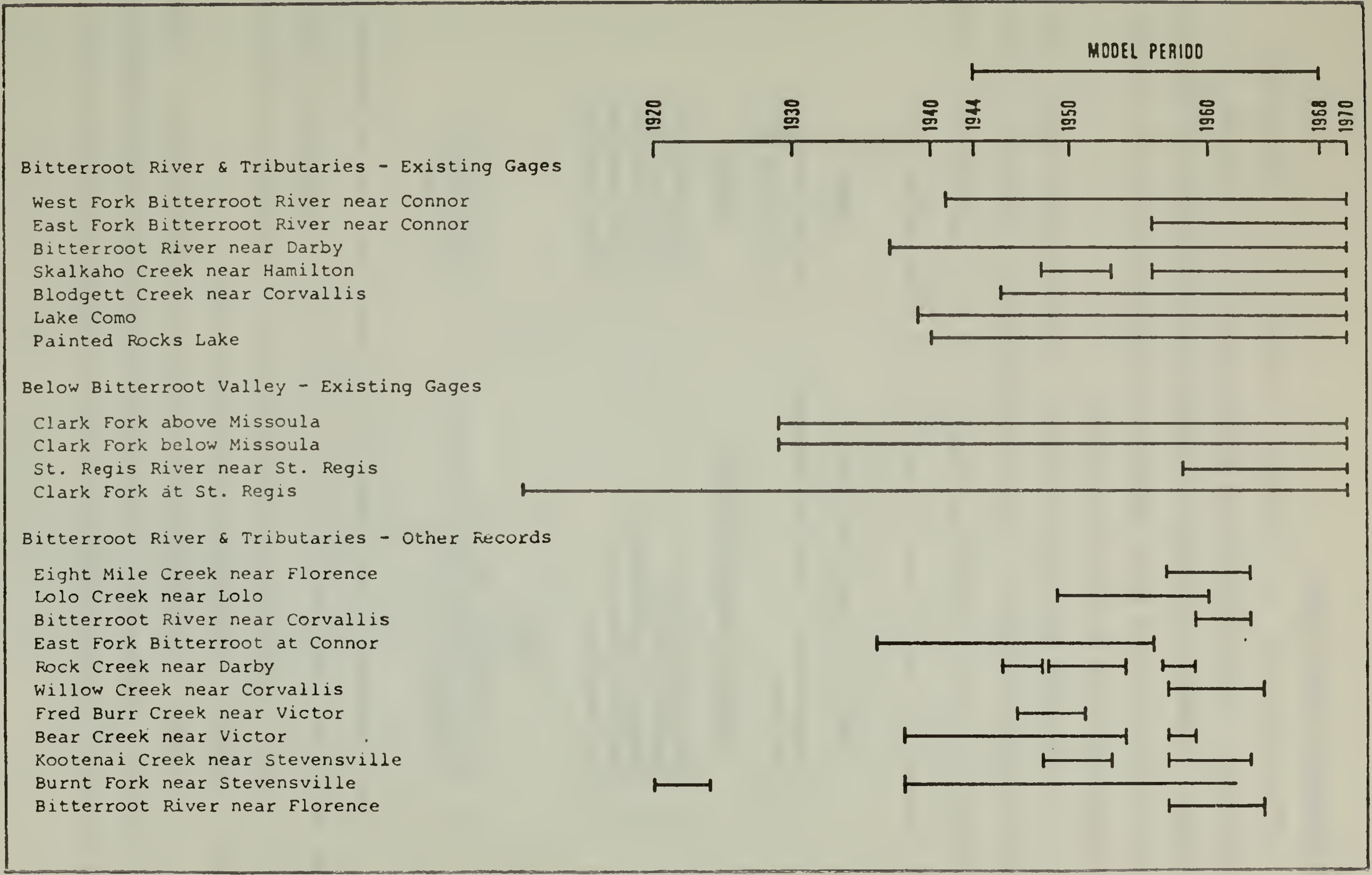
Preparation of Hydrologic Data

Preparation of data in a suitable form for a simulation model constitutes a large part of the actual effort that will go into the model. This task involves taking the historic data, as recorded, and processing it giving due consideration to any regulation that may have been made. In most regions of this country, some flow regulation will almost certainly have taken place during the period of record, and from the recorded flows unregulated or natural flows must be estimated. The aim of this procedure is to put all of the streamflow on the same basis to produce a statistically homogenous population. This means the effect of gradual changes in water use or even land development must be allowed for. If the condition which all of the flows are converted to is the original condition of the area, the reconstituted flows are called "virgin flows". If the reference condition is the present level of development, the result is called "natural flows".

In the Bitterroot Valley there has been major regulation by only two reservoirs, Painted Rocks and Lake Como. It was necessary to work backwards from both streamflow and storage records to remove regulation effects. Regulation by numerous small reservoirs on various tributaries could not be accounted for due to lack of sufficient information. This error is not felt to be significant when one considers that inaccuracies in actual measured streamflow may exceed in magnitude the capacity of many of these storages. Since it was impossible to remove all regulation effects, the flow conditions used in the model are "natural flows".

Natural streamflow data available is shown in Table 1. The period of flow record used in the model is the 25 year period, 1944-1968. From Table 1, it may appear that there is ample streamflow data to construct a model, but there exist many gaps in certain records and many records are not of concurrent length. In addition, there are no flow records for most of the numerous west side tributaries. To completely account for all available streamflow, the gaps in existing records had to be filled in and estimates had to be made for tributaries for which there are no records. To accomplish the first task, a computer program developed by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers was used. This program enables one to fill in missing data by cross and serial correlation with other complete streamflow records. The best records available for filling in missing data are those of the East and West Forks of the Bitterroot River near Connor. Since these records reflect only minor influence of man's activity (which can be adjusted for), they were used as the key stations to fill in and extend other records in Table 1. After all existing records were filled in and extended, approximately 70 percent of the measured flow was accounted for, leaving 30 percent to be estimated. Estimates of flow for ungaged tributaries were made from existing records and comparisons of drainage areas. This was accomplished using a regression equation for west side tributaries and a similar equation for ungaged east side tributaries.

TABLE 1 PERIOD OF STREAM DISCHARGE RECORD



Definition of System Design

The system extent and the hydrologic data both relate to the problem to be solved, but the simulation process has as its objectives the evaluation of a design or a management procedure or perhaps both. Data about the system design and the limiting values on the parameters of the design were needed so as to delineate the range of decisions possible.

For this study the measure of how well a particular system design or management scheme fulfills the irrigation requirement under various levels of development was used to evaluate performance. The system was examined considering Bitterroot Valley as previously defined with the following features:

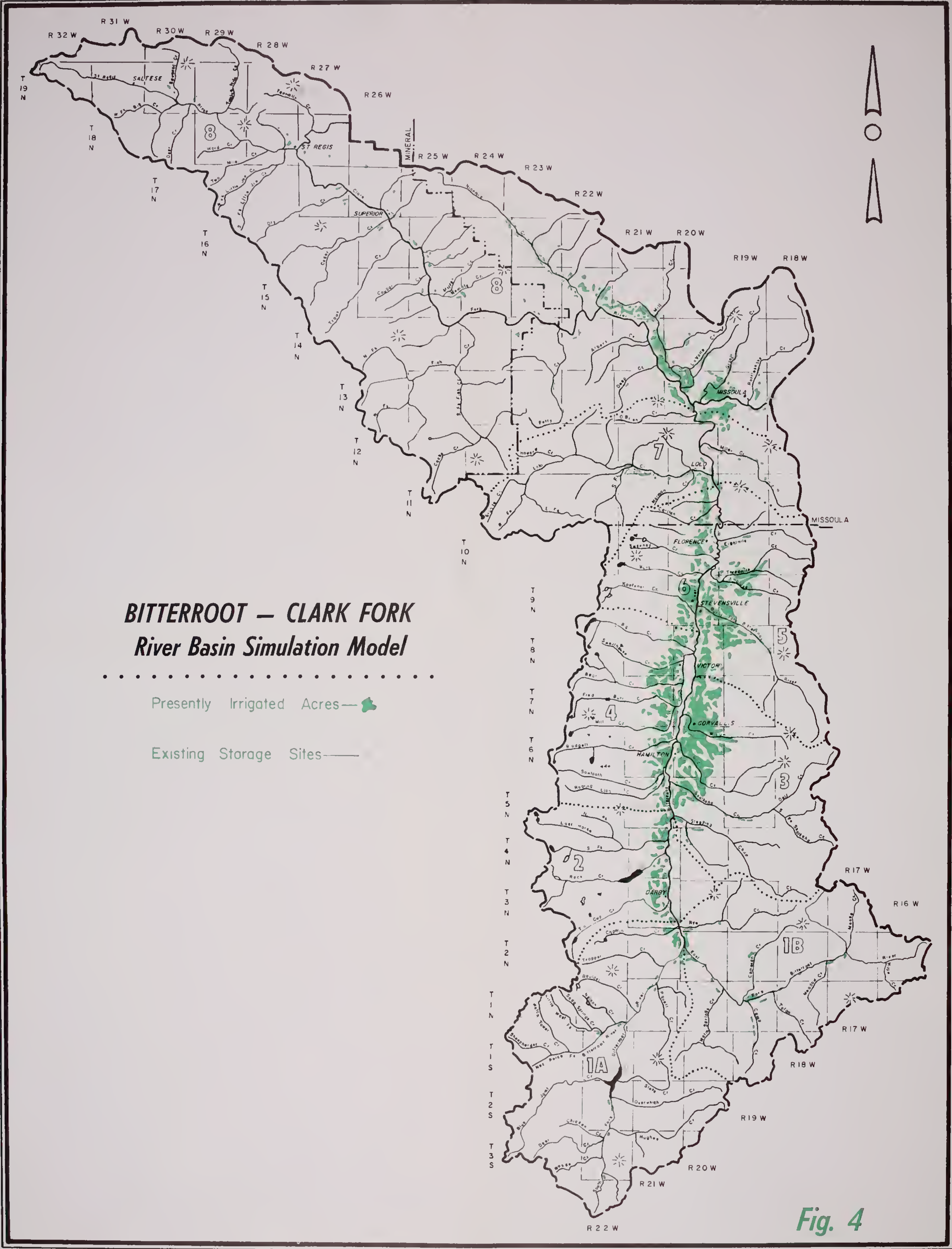
Existing Storage Facilities	Capacity
1. Painted Rocks (West Fork Reservoir)	32,000 acre-feet
2. Lake Como	33,000 acre-feet

Proposed Storage Facilities	Capacity
1. Upper Sula Reservoir	60,000 acre-feet
2. Expanded Lake Como	53,600 acre-feet
3. Blodgett Creek Reservoir	10,500 acre-feet
4. Burnt Fork Reservoir	13,000 acre-feet
5. Lolo Reservoir	135,000 acre-feet

Canals	
1. All existing canals	unconstrained
2. Proposed Westside Highline Canal	unconstrained
3. Proposed Woodside Canal	unconstrained

Land classification data (Table 2) was gathered from summaries prepared by the Montana Water Resources Board and the U.S. Bureau of Reclamation. Figures 4 and 5 show both existing and potentially irrigable areas within the study area and Table 2 provides a breakdown by subarea of these acres.

In subarea 1, potentially irrigable new land totals 7,394 acres, a large part of which lies in subarea 1B. There are currently some 6,060 acres of presently irrigated land in the East Fork and West Fork of the Bitterroot River valleys.



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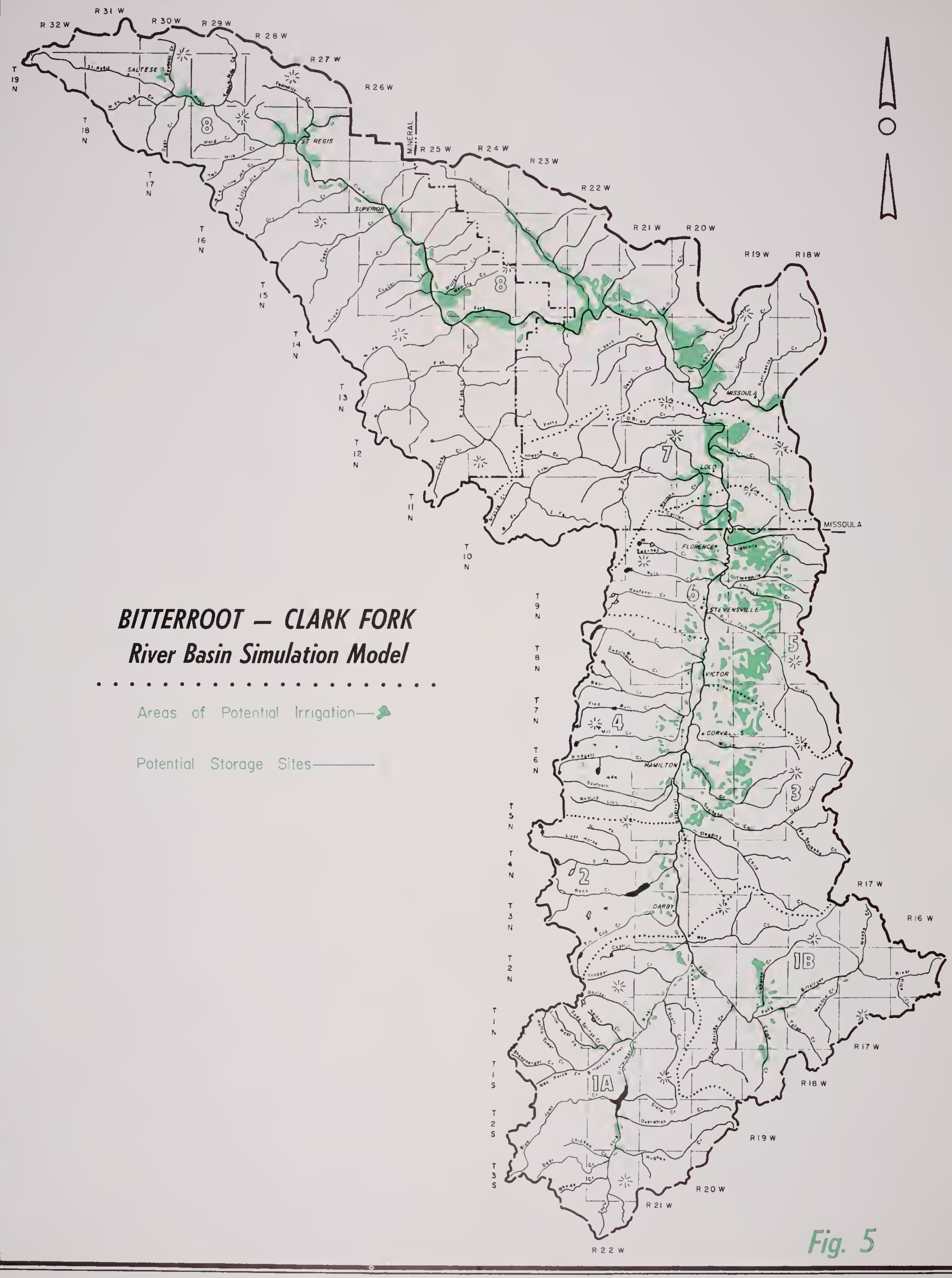
Presently Irrigated Acres — ▨

Existing Storage Sites ——

Fig. 4



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……

Areas of Potential Irrigation—🟩

Potential Storage Sites———

Fig. 5

There are 8,238 acres of presently irrigated land in subarea 2, and only 2,052 acres of potentially irrigable new land in this area, most of which could be irrigated if systems were available.

Subarea 3 contains the largest amount of land - 31,228 acres - presently under irrigation in any of the subareas. Also available for irrigation are 15,300 acres of new land, but because of the limited water supply available within the subarea, the amount of irrigable land considered for irrigation becomes greatly reduced.

Subarea 4 contains 20,976 acres of irrigated land which, under existing conditions, experience water shortages in the later part of the irrigation season.

The proposed distribution system for the west side of the valley would provide supplemental water to existing irrigation and benefit the 3,865 acres of new land in the subarea.

Subarea 5 contains another large area of existing irrigation (27,340 acres) and the largest area of potentially irrigable lands (25,724 acres) in the valley.

The proposed reservoir in this subarea would provide supplemental late season irrigation water for some presently irrigated land and a partial supply for 11,000 acres of the irrigable land in the subarea.

Subarea 6 has historically suffered late season irrigation shortages due to almost total dependence on natural stream flow and supply for 11,979 acres of presently irrigated land. The proposed Woodside Canal would provide supplemental irrigation water to almost all irrigated lands and 6,676 acres of potentially irrigable land in this subarea.

There are only minor amounts of irrigated land (3,200 acres) in subarea 7. There are 10,233 acres of potentially irrigable lands in this subarea, some of which lies on the eastern side of the area and would be hard to reach with irrigation water.

This accounts for a total of 109,021 acres of irrigated lands in the study area and 71,234 acres of potentially irrigable lands.

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TABLE 2. Land Classification

Area	Presently Irrigated Land (Acres)	Potentially Irrigable Land (Acres)
1	6,060	7,394
2	8,238	2,052
3	31,228	15,300
4	20,976	3,865
5	27,340	25,724
6	11,979	6,676
7	3,200	10,223
TOTAL	109,021	71,234

Operating Procedure

The rules under which a system and hence a model of that system will be operated are the most important part of the data needed to use a simulation model. For each possible configuration of the system there is an optimum operating policy, although it is most likely that for the modeling and possibly real life purposes, an approximation of this, determined by careful judgment, will have to suffice.

The particular configuration run to demonstrate the validity of the type of approach is shown in Figure 6. The operating procedure is in general as follows:

For each subarea:

1) Calculate monthly demand for a given level of development.

2) Examine possible sources of supply.

3) If natural inflow is sufficient, deplete the natural inflow by the amount required.

4) If the natural inflow is insufficient, check possible diversions from either the main stream or storage facilities.

5) Deplete the secondary source by the difference between demand and natural inflow for the subarea.

6) If natural flow in a tributary for a subarea is in excess of its own monthly demand and downstream demands, excess may be stored up to the capacity of any existing or potential storage facility located on that tributary.

Figure 6 schematically shows the system layout with subareas, storage facilities ③, releases from storage (REL), diversion points (DIV.), return flows (RET.), and major canals designated. In the actual computer program several subareas were further subdivided due to either additions to or reductions in the possible sources of supply within the particular subarea.

The demand for water in an area was calculated using the acreage under cultivation and diversion requirement shown in Table 3.

TABLE 3

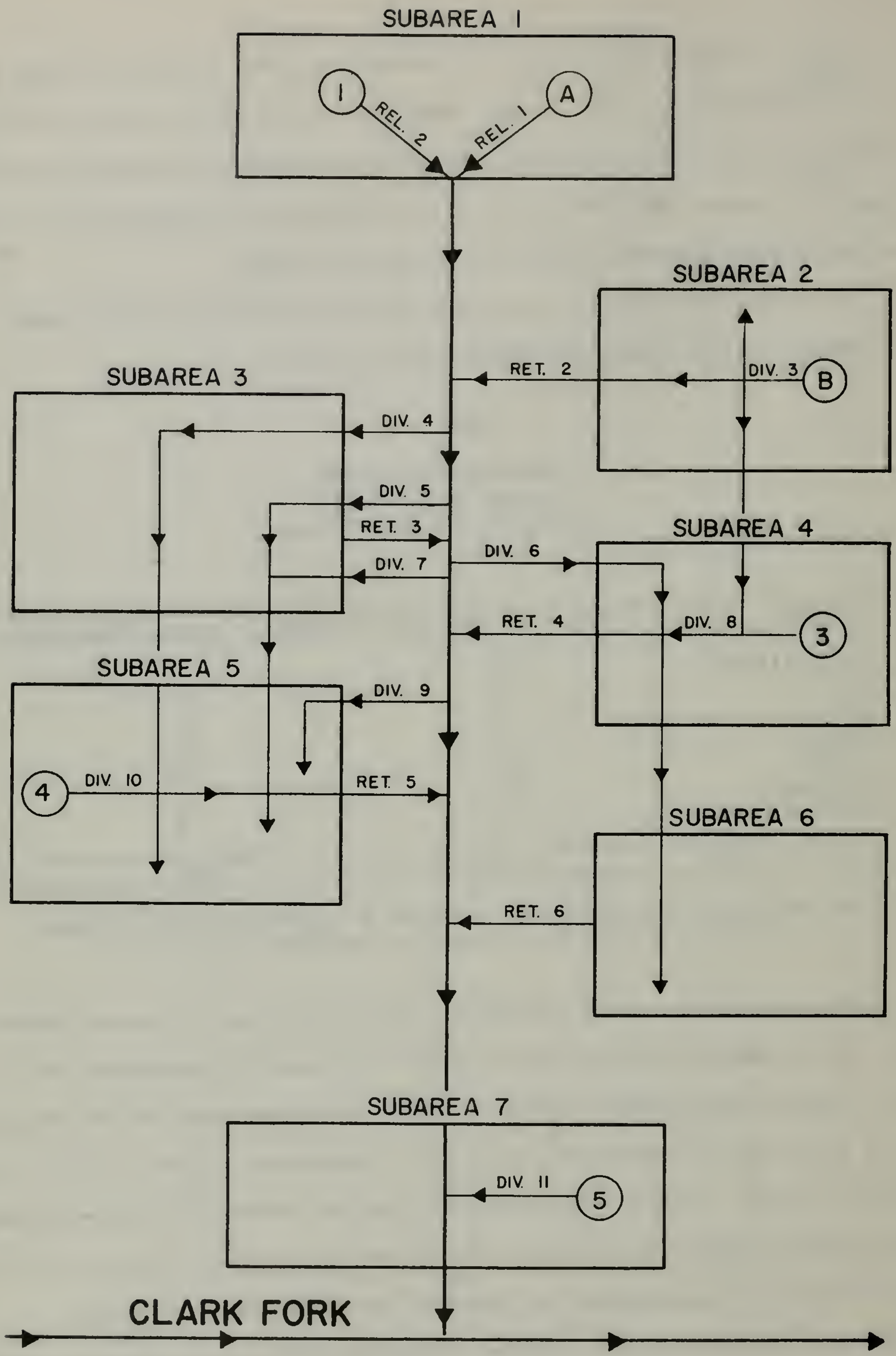
DIVERSION REQUIREMENT
Monthly Distribution
Bitterroot Valley, Montana

Month	Acre-Feet Per Acre	Percent of Annual Requirement
April (15-30)	0.2	5
May	0.7	16
June	0.9	20
July	1.1	24
August	0.9	20
September	0.5	11
October (1-15)	0.2	4
TOTAL	4.5	100

ref. Bitterroot Valley Project, Montana, A Supplement to the Columbia River Basin Report, U. S. Bureau of Reclamation, May 1949.

This demand was derived using consumptive use and allowing a 45 percent return flow. It was assumed that the actual demand would satisfy requirements for further irrigation development. This theoretical demand was used for all areas within the study area and checks well with actual diversions for areas served by the Bitterroot Canal. A second check on the irrigation efficiency was made by examining data prepared by the U. S. Geological Survey which indicates a net water loss within the Valley of approximately 2.5 acre-feet per acre of land irrigated.

Storage facilities will be operated at various levels of performance, utilizing varying capacities of storage depending upon the demand for irrigation water.



OPERATING PROCEDURE

FIGURE 6

In this manner, it will be possible to determine the need for additional storage and the alternatives of reservoir management.

Operating Results to be Achieved

The results from several simulation runs have been studied and preparations are being made to utilize additional constraints and change the assumptions to be used in successive runs. Using several varying aspects of water storage projects and delivery systems, the Board's planning staff hopes to be able to establish reliable statistics showing the demand for water on both existing and potentially irrigable lands. Then, adding consideration of other aspects of water development and use, these will be considered for additional development of the model.

The simulation runs made to date, verify the validity of this type of approach to water resources planning. The results show that existing facilities together with the proposed facilities included in the model would provide an adequate irrigation supply at all levels of development considered with only the minor exceptions noted.

The examples considered are but two of the many alternative designs which may be examined using the technique described. It may be desirable to examine many different combinations of design and operating criteria to determine interaction among parts of the system and to determine the optimum combination for the particular objective studied.

Again, detailed simulation of the lower Clark Fork River Basin would be an effort in itself and should consider all upstream drainage in such a study.

Many of the potentially irrigable lands lying on the Clark Fork below Missoula require a 150-500 foot pump lift to high benches above the river. Therefore, problems such as this will also have to be considered. There is presently an adequate supply of water to irrigate the potential land areas, but it would require extensive water distribution systems to irrigate these high benches.

CONCLUSION

Following development of this particular modeling approach to river basin planning, the staff of the Montana Water Resources Board plans to utilize this type of modeling approach for other river basins in Montana. The findings of this and future studies will not in any way economically justify development of water or land use projects, but will be used in the water needs study from which requirements and projections will be made for future use of Montana's water and land resources.

As was stated before, planning for maximum irrigation development is only one aspect of water utilization. Given more time and effort, additional data can be utilized to produce in-depth studies on all facets of water use, from industrial and municipal to stockwater and domestic.

CONJUNCTIVE USE OF GROUNDWATER AS AN ALTERNATIVE TO SURFACE STORAGE

Because of the seasonal nature of streamflow and water availability, additional storage and diversion projects will be required to support any further irrigated land development in the Bitterroot Valley with a firm water supply. The simulation model which has been constructed hypothesizes various levels of additional land development and determines the surface water storage requirements necessary to support such increases. An alternative to construction of new storage works or expansion of existing facilities is to develop the available ground water resources. This could be accomplished as a mutually exclusive alternative or in conjunction with new surface reservoirs.

Too often ground water is viewed solely as a source of water and proper recognition is not given to the aquifer system's ability to act as a storage reservoir, a water transmission system, and as a stream flow regulator. Given proper geologic conditions and careful planning it is possible to utilize all of the aquifer functions at a considerable increase in water resource system development efficiency.

Conjunctive use management of aquifers and surface reservoirs has been studied and discussed by many people such as [1]Domenico, [2]Buras, [3]Hall, and [4]Burt.

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1. Domenico, P.A.,"Valuation of a Ground-Water Supply for Management and Development," CWRR, DRI, U of N, Tech. Report Series H-W Hydrology and Water Resources Pub. No. 3, Reno, Nevada July 1967.

   Domenico, P.A., "Economic Aspects of Ground Water Use to Stabilize the Water Supply", Humboldt River Studies, CWRR, DRI, UNS, Project Report No. 10, Reno, July 1968.

2. Buras, N., "Conjunctive Operation of Dams and Aquifers", Proc. ASCE, Journal of Hydraulics Division, November 1963.

   Buras, N., "A Three-dimensional Optimization Problem in Water-resources Engineering", Operational Research Quarterly, V. 16, No. 4.

3. Hall, W.A., and Buras, N., "An Analysis of Reservoir Capacity Requirements for Conjunctive Use of Surface and Groundwater Storage", I.A.S.H. Pub. No. 57, Groundwater in Arid Zones, p. 556-563, 1961.

However, most of the studies reported upon have been of the operational nature, i.e. development of optimum operating rules to schedule surface water releases as a function of water stored above, and below, ground and streamflow. Studies dealing with the development of such systems to meet a specified planning objective or criteria are far less common.

Most conjunctive use studies have considered reservoir releases to go either to direct irrigation or to be diverted into a ground water recharge facility. Nowhere it seems, has a well field been considered in its ability to directly divert active streamflow. The extent to which this may happen is directly related to the degree of interconnection between the stream and aquifer system. Given a situation where there are no impermeable strata between the river channel bottom and the aquifer system and the ground water level is below the channel bottom, the rate of infiltration to the aquifer will be a function of streamflow through two mechanisms; head differences and channel bottom condition. Generally the infiltration rate will be higher during high flow periods than low flow periods. During high flow there is a greater head difference between the stream and aquifer and the channel bottom is being scoured and no silt deposition occurs. During low flow the head difference is smaller and siltation of the channel bottom occurs thus reducing the permeability.

The relationships between stream and aquifer can be used to an advantage to provide a firm water supply and to aid in flood control. By utilizing spring and early summer runoff for direct irrigation and ground water for late season irrigation, a cycle can be created whereby the high spring runoff refills the aquifers and at the same time reduces that runoff. This stored water then is available for the next late season irrigation period.

The U. S. Geological Survey has found that in the Bitterroot Valley there is a high degree of interconnection between the flood plain alluvial material and the

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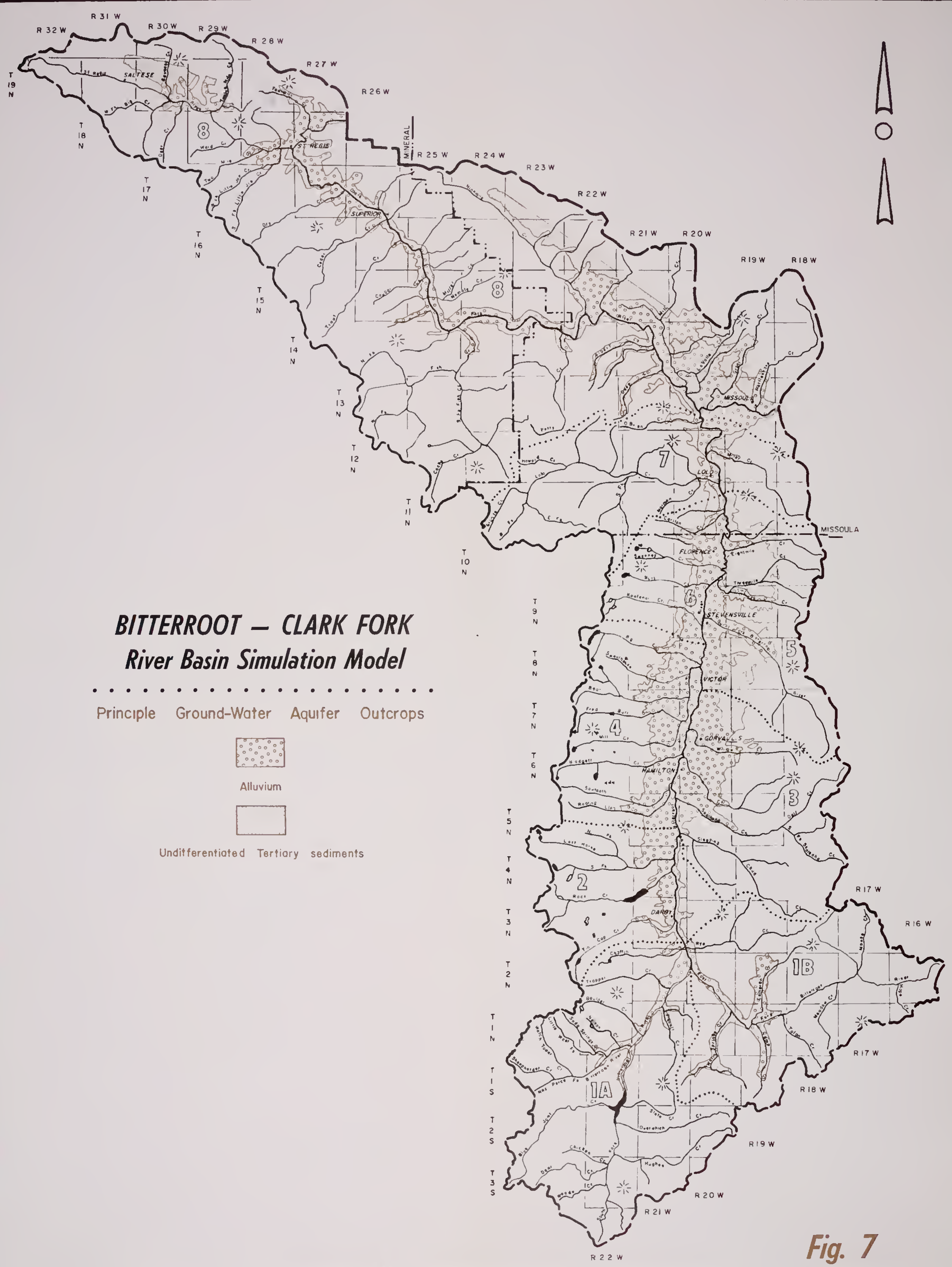
4. Burt, Oscar R., "The Economics of Conjunctive Use of Ground and Surface Water", Hilgardia, V. 36, No. 2, p. 31-111, 1964.



BITTERROOT — CLARK FORK
River Basin Simulation Model

Fig. 7

river. The extent of these aquifer materials is shown in Figure 7. Transmissivity values computed for these aquifers range from 20,000 to 300,000 gallons per day per foot. These characteristics are very favorable to development of a significant ground water supply. At one point in the USGS report the authors cautioned against ground water development as it would serve to deplete streamflow; this is the characteristic which will make conjunctive use practical.

By proper and careful, but not extensive, alteration of the simulation model which has been developed it may be possible to:

a) select the most desirable area or areas for ground water development

b) determine the necessary level of development at each site in terms of overall efficiency and planning objectives, and

c) determine the effect of ground water development on peak period runoff

By incorporating the revised simulation model in an optimization algorithm, it may be possible to select the combination of surface storage reservoirs and level of ground water development which meets the planning objectives with maximum economic efficiency. Because of the very limited time available to develop the model presented in this study, it was infeasible to employ the ground water alternative as discussed here or to incorporate the model into an optimization routine.

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